3D ICEPIC Simulations of a Pulsed Relativistic Magnetron with Transparent Cathode: A Comparative Study

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Abstract

Ongoing research at the University of New Mexico (UNM) shows significant improvement in the start and rate-of-build-up of microwave oscillations in a relativistic magnetron driven by a transparent cathode [1,2]. Nearly all simulation work on this cathode to-date has been carried out utilizing the MAGIC particle-in-cell (PIC) code.

Simulations of the A6 magnetron with transparent cathode using the 3-dimensional code Improved Concurrent Electromagnetic Particle-In-Cell (ICEPIC) at the Air Force Research Lab (AFRL) were carried out to examine the performance of the transparent code and compare with results from MAGIC. Output parameters such as microwave power, microwave frequency and anode current all as function of axial magnetic field are presented and compared with the MAGIC results.

I. INTRODUCTION

High power microwave (HPM) devices are necessary for a number of applications including radar and communications. The relativistic magnetron, a cross-field device, is one of the most compact, powerful, and agile HPM sources today. These devices are capable of high output power (GW-class) with applications over a wide range of frequencies. However, for applications where short pulse high peak power is desired, the relativistic magnetron, equipped with a traditional solid cathode, has several performance deficiencies. Among them are the oscillation start time, the rate at which oscillations build, mode competition and finally the RF output power efficiency. The non-relativistic magnetron has operated at efficiencies of nearly 90%; the relativistic magnetron, however, has operated with efficiency in the range of about 30% [1]. Research at UNM and the University of Michigan (UM) has been directed at performance improvements in output power, efficiency, and mode purity in relativistic magnetrons. One method that has demonstrated magnetron performance improvement is priming, which includes magnetic priming, cathode priming, and electrostatic priming. The transparent cathode, invented at UNM, provides better start conditions, faster rate-of-build-up of oscillations and better output characteristics. The numerical work that has been carried out using MAGIC, demonstrates that the transparent cathode is capable of fast start-up (immediate upon voltage ramp up), single mode operation with significant mitigation of mode competition, and an increase in RF efficiency [2-6].

Design and development of technologies hinge on the close collaboration of theory, simulation, and experiment. Computational techniques are a critical component of the research and design process, which is especially crucial for electromagnetic engineering systems where solutions to Maxwell's equations in complex geometries are difficult to solve. In the past advances were gained through experimentation, which is expensive and time consuming. Simulation provides many benefits such as shorter turnaround time, unlimited diagnostic capabilities, and a controlled environment.

The work here seeks to compare the performance of the transparent cathode in an A6 magnetron using two PIC codes: ICEPIC and MAGIC. Other than the paper by Fleming & Mardahl [7] the bulk of the simulation work for the transparent cathode has been carried out with a single PIC algorithm MAGIC.

A. Basic Magnetron Operation

Relativistic magnetrons such as the A6 are capable of output power on the order of 1 GW, drawing 10's kA currents, and pulse widths constrained by the pulsed power supply. The relativistic A6 magnetron is a cross-field device that is coaxial in geometry, consisting of an inner cathode and an outer multi-resonator anode. Periodic vane structures exist along the anode block and serve as resonators and comprise a slow wave structure. An externally supplied voltage is applied between the cathode and the anode. Electrons are emitted from the cathode in an explosive electron field emission process. The electrons emitted are subjected to an external magnetic field Bz if this magnetic field is less than the

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14. ABSTRACT
Ongoing research at the University of New Mexico (UNM) shows significant improvement in the start and rate-of-build-up of microwave oscillations in a relativistic magnetron driven by a transparent cathode [1,2]. Nearly all simulation work on this cathode to-date has been carried out utilizing the MAGIC particle-in-cell (PIC) code. Simulations of the A6 magnetron with transparent cathode using the 3-dimensional code Improved Concurrent Electromagnetic Particle-In-Cell (ICEPIC) at the Air Force Research Lab (AFRL) were carried out to examine the performance of the transparent code and compare with results from MAGIC. Output parameters such as microwave power, microwave frequency and anode current all as function of axial magnetic field are presented and compared with the MAGIC results.

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Hull cut-off condition at a given voltage electrons may not be insulated and a net current can be drawn across the gap. The Hull condition B* provides a threshold for magnetic insulation in which steady state can occur. As Bz increases to greater than the Hull condition Bz > B* there is a thresh hold at which the drift velocity decreases and the space charge is no longer in synchronism. At this threshold, the Bunemann-Hartree condition, oscillations will no longer exist. The electrons are also subjected to a radial electric field that is perpendicular to the magnetic field and thus the electrons acquire an $E \, x \, B$ drift velocity. If this drift velocity is approximately equal to the phase velocity of the ambient RF wave the electrons exchange energy with the wave and thus convert the electron potential energy into RF energy. This interaction allows the electrons to cross the anode-cathode gap (AK-gap) and, depending on the frequency and mode that is excited, will have a distinctive field distribution within the cavity. [8]

B. Transparent Cathode

Present applications not only require high power but also fast start of oscillations. Oscillations are very slow to start via noise. The start time for oscillation is dependent on two factors: the start condition and the rate of build up. Extensive research has been carried out to improve the performance of the relativistic magnetron. The focus has been to identify techniques to provide rapid start of oscillations which has resulted in various techniques for priming: cathode priming, magnetic priming, and RF priming. Cathode priming involves the specific geometry of the solid cathode; azimuthally periodic structures on the cathode are prepared to be discrete electron emitting regions therefore providing a pre-bunched electron cloud in a desired mode. This specific priming technique has shown to provide fast start up, suppression of mode competition, and single mode operation for the UM relativistic magnetron [9]. Magnetic priming introduces a perturbed magnetic field by use of small permanent magnets placed outside of the magnetron anode block, providing an azimuthally varying magnetic field. This technique of priming has shown to provide suppression of noise, rapid mode growth, and single mode operation in the pi-mode for the UM relativistic magnetron. However there is an increase in the weight and volume of the device [10].

The transparent cathode, which is comprised of a thin walled hollow cylinder with periodic strips removed axially (see figure 1), yields performance improvement by self-consistently providing three different priming techniques: cathode priming, magnetic priming, and electrostatic priming [5]. The transparent cathode also has the added benefit of the faster rate of RF field buildup which is achieved through higher amplitude E_Θ acting on the electrons giving them a greater velocity. With a solid cathode E_Θ goes to zero on the surface of the cathode while with a transparent cathode E_Θ decreases to zero on axis [5,6].

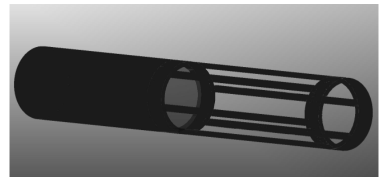

Figure 1. CAD preprocessing depiction of transparent cathode.

Through experiments and simulations at UNM the transparent cathode has self consistently shown improvement of start conditions, faster rate-of-build-up, and improvement in the output characteristics. UNM has achieved high radiated power on the order of 1 GW, high electronic efficiency and a very stable microwave generation over a wide range of magnetic fields. [5]

II. SIMULATION METHOD

A. ICEPIC

ICEPIC is massively parallel three dimensional Cartesian PIC code developed at AFRL. ICEPIC solves Maxwell's equations and the relativistic Lorenz force equation with a fixed staggered grid to difference and advance, in time, Faraday's law (Eq. (1)) and Ampere's law (Eq. (2)) using the Yee technique.

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - \mathbf{J} \qquad (1)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E} \qquad (2)$$

E and **J** are located on the primary cells edges while **B** fields are on the cells faces. The fields are advanced forward in time with a leapfrog method.

Momenta and positions of particles are updated via the Lorenz force law (Eq. (3)) using the Boris relativistic particle push. The new velocities and positions are updated by way of the leapfrog method.

$$\mathbf{F} = m\frac{d\gamma\mathbf{v}}{dt} = q\left(\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B}\right) \qquad (3)$$

Current and charge densities are evaluated from the new velocities and position using Villasenor and Buneman's charge conserving current weighting algorithm. Once the field equations, charge density, and current are updated on the grid the loop can start again. ICEPIC is run on parallel architecture and to run efficiently uses a dynamic load balancing scheme this way particles and field data can be evenly allocated between all the CPU's. This helps to alleviate heavy computational burden on one machine. [11]

B. Simulation Set Up

The transparent cathode was simulated with the A6 magnetron design, which consists of a cylindrical anode structure of axial length of 7.2 cm, anode radius of 2.11 cm, and cavity radius of 4.11 cm. The cavity angular width is 20º while the vane structure is 40º. The transparent cathode is a thin walled cylindrical structure with a cathode radius of 1.58 cm and wall thickness of 2 mm. The strips are periodically arranged at 60º of separation with an angular width of 10º. Figure 2 is the transparent cathode as modeled in ICEPIC.

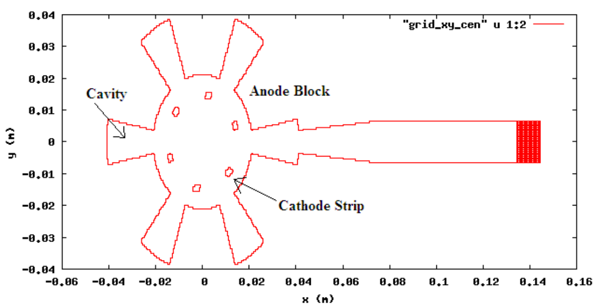

Figure 2. Grid plot of the transparent cathode with A6 magnetron.

We use ICEPIC to simulate the A6 relativistic magnetron, which includes the entire magnetron along with the interaction region, the waveguide with perfectly matched layer (PML) boundary condition where power is extracted, the cathode where particles are emitted, and the downstream cathode shank that connects to the pulsed power system. The simulations are carried out using a grid resolution of dx = 0.5 mm. The resolution of the interaction region is important for convergence of a solution. We are well resolved with an interaction region of 0.53 m and a frequency of 4.0 GHz. Studies in the literature showed simulations have been performed to study convergence when analyzing the A6 driven by a transparent cathode [7]. The convergence studies performed previously at AFRL had shown that dx =0.75 mm for the interaction region was sufficient [10]. At a resolution of 0.5 mm our grid volume in the x-direction is 608 cells, in the y-direction 608 cells, and in the z-direction 637 cells for a total of 235,475,968 cells. Our simulations were run on 64 x 3.0 GHz Intel Woodcrest CPUs of an Advanced Technology Cluster. Each simulation took approximately 24 hours. At saturation our simulation contains approximately 16 million particles. These particles are emitted via a space-charge-limited field emission algorithm. The axial length set to emit is 10.2 cm along the z-direction at z = -0.056 m and ending at z = 0.046 m.

The emission threshold was uniform across the entire surface and was set to emit when the normal electric field exceeded 2×10^7 V/m. The space-charge-limited algorithm was used such that the amount of charge emitted was sufficient to negate the electric field along the surface for each time step [1].

A voltage signal is applied via a boundary condition on the most upstream end of the model where the pulsed power pulse forming line would be located. The pulsed power system has not been included in the simulation; rather, it is emulated by the Poisson solution. The Poisson solution establishes a potential at the boundary that then propagates down the cylinder, thus creating a diode voltage throughout the magnetron. The pulse is established as a linear 1 ns ramp followed by a constant flat top for the remainder of the simulation. The simulations presented here extend to 90 ns. A uniform axial magnetic field was applied throughout to simulate the external coils used in the experiment [1].

C. Results

The simulations carried out at UNM using MAGIC were conducted with a constant voltage of 350 kV. When implementing a magnetic field scan MAGIC uses an algorithm that holds the voltage constant at the input port for each magnetic field imposed. ICEPIC does not possess this capability. In ICEPIC, when the Poisson solve was applied at 350 kV the voltage that was measured at the input varied due to reflections and different values of magnetic field as the simulation parameter scan proceeded. In order for us to make a direct comparison with MAGIC's results we ran numerous simulations requiring 100's of simulation hours at varying voltages and varying magnetic fields then sampled the simulations that ran at an observed 350 kV.

Figure 6 shows the range of magnetic field over which 2π mode oscillations take place at 350 kV for ICEPIC generated data. For comparison we have a similar graph (figure 7) using data points from UNM with magnetic field varying from 0.60 T to 0.68 T. We have extracted RF power through a waveguide terminated with a PML. RF power is evaluated via the area integral of the outward Poynting flux. We obtained a peak measured output power of 800 MW while MAGIC consistently obtained 1 GW. The power obtained in MAGIC and the power obtained in ICEPIC differs by about about 200 MW, which is still within 20% (see figures 6 and 7).

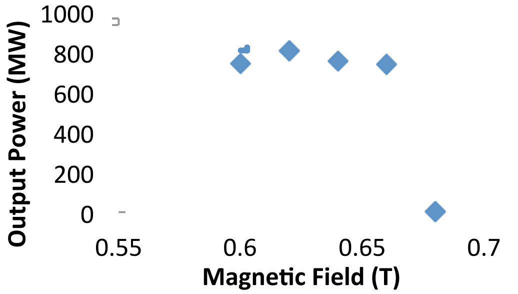

Figure 6. Magnetic field scan obtained from ICEPIC data.

For magnetic fields greater than 0.66 T and at 350 kV, MAGIC continues to yield an RF output power of ~1 GW. Unlike the results from MAGIC, there is a sharp decrease in output power beyond 0.66 T. This drop off in RF power is due to a rise in mode competition. Beyond B = 0.66 T, the 2π mode is no longer dominant. To facilitate a direct comparison with MAGIC we sampled five simulations with varying magnetic field at voltage ~350 kV. The B=0.62 T simulation is chosen as a reference that typifies magnetron performance for the other simulations that successfully ran in the 2π mode. Figure 8 is a measurement of the output power as a function of time for this reference. The mean RF output power is 800 MW.

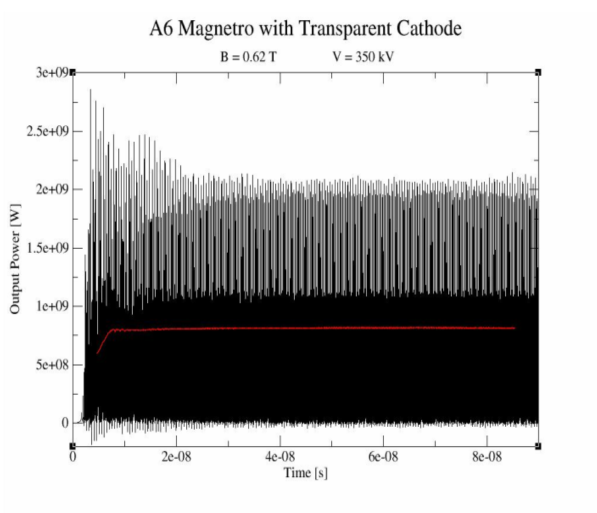

Figure 8. Mean RF output power is 800 MW in ICEPIC simulations.

The input voltage is determined by integrating the electric field radially from cathode to anode near the upstream point at which the Poisson boundary condition is applied. Figure 9 presents a typical voltage profile for a magnetic field of 0.62 T. The red line indicates a time average diode voltage of 350 kV.

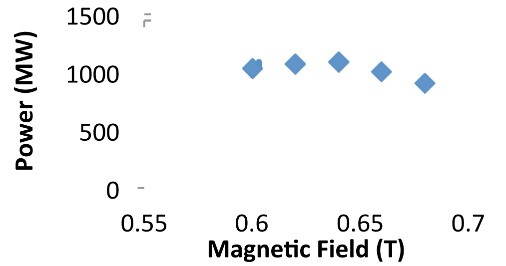

Figure 7. Magnetic field scan from MAGIC simulations.

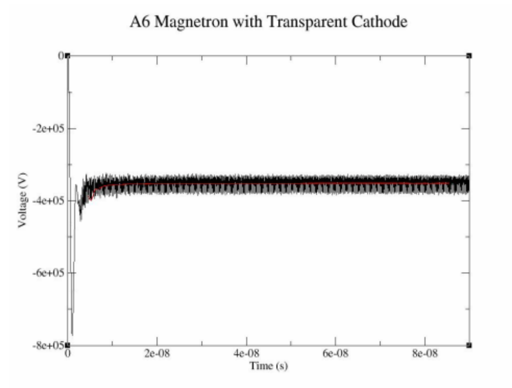

Figure 9. Voltage averaged over time in ICEPIC simulations.

The time history of mode amplitudes is presented in figure 10. The time history of the voltage between each vane structure of the SWS is recorded. A discrete Fourier transform configuration to wave-vector space is then used to extract the modes present in the interaction region. We confirm that the A6 magnetron with transparent cathode is dominated by the 2π-mode at 4.0 GHz. We can also see by the graph there is an immediate mode excitation into the 2π-mode before 5 ns. Mode excitation is similar for the other high RF output power simulations.

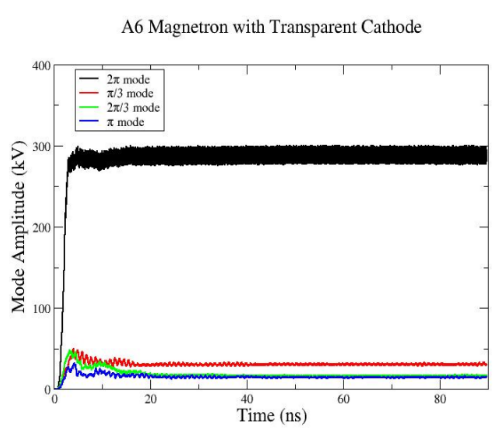

Figure 10. Mode amplitude plot over time from ICEPIC simulations.

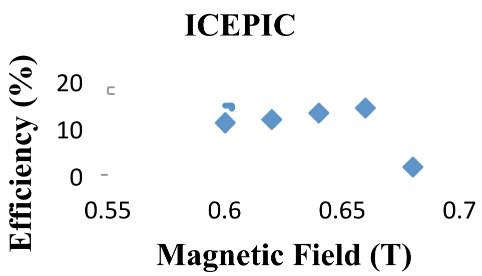

Figure 11. Efficiency as function of magnetic field from ICEPIC simulations.

Electronic efficiency for our ICEPIC model is determined by the ratio of input power to RF output power. The input power is calculated as $P = I\ V,$ which is determined by the input current supplied to the cathode, I and the input voltage, V. ICEPIC uses a current diagnostics that integrates B around a circle to determine the total current traveling through that circle. In our simulation this is placed at the end of the chamber to determine current loss. ICEPIC also has a diagnostic that measures the time history of current that is determined by the charge passing through a surface; in our simulation this is the anode current. The two currents together provide us with total current I. The voltage V is the measured input voltage, discussed earlier, as the Poisson boundary condition. The reference simulation at a magnetic field of 0.62 T with a measured 350 kV yields an RF output efficiency of 11.7%, which is typical of our sampled data. It is at a magnetic field of 0.68 T at which we see a sharp decline in RF output and efficiency that diverges from the results obtained in MAGIC simulations.

III. DISCUSSION

ICEPIC and MAGIC simulations of the A6 magnetron with transparent cathode yielded agreement on several key magnetron performance measures such as 2π mode dominance as well as oscillations at 4 GHz. We were able to confirm that immediate spoke formation took place and was stable over a wide range of magnetic fields. However, there remain several outstanding issues. ICEPIC has shown RF output power of 800 MW with efficiencies of ~12%, which has consistently remained lower than the results from MAGIC. Additionally, mode competition eradicated significant RF power output for ICEPIC simulations at a magnetic field above 0.66 T. No drop off was observed in MAGIC simulations at 350 kV. Such a drop-off does exist in MAGIC data generated at 250 kV [12]. Additionally, it must be noted that MAGIC simulations were conducted in cylindrical coordinates whereas the ICEPIC simulations were on a Cartesian mesh. Asymmetry associated with Cartesian gridding of the magnetron may act to excite other modes in the simulation and thus bring about the power drop-off.

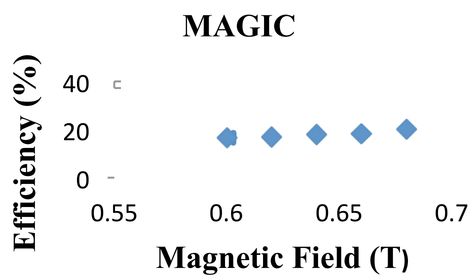

Figure 12. Efficiency as a function of magnetic field from MAGIC simulations.

Indeed, this may also be the cause of the RF output power failing to reach 1 GW for all simulations examined here. Under resolved ICEPIC simulations of the UM magnetron with transparent cathode yielded mode competition that was later eradicated upon a doubling of resolution [13]. A similar process may be at work here. Two avenues are open to address this problem. A convergence study must be performed when small scale structures such as the elements of the transparent cathode are present. This will establish a minimum resolution at which spurious artifact-driven modes may be suppressed. Additionally, to facilitate a more direct comparison between MAGIC and ICEPIC simulations future ICEPIC simulations in cylindrical coordinates will be performed. This feature in ICEPIC has now reached a sufficient level of maturity and robustness that production simulations may now be undertaken.

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